

Fall cone test on biopolymer-treated clay

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Abstract. Fall cone tests were conducted to evaluate the consistency variations of clay soils treated with six types of biopolymers, e.g. carrageenan kappa gum (KG), locust bean gum (BG), xanthan gum (XG), agar gum (AG), guar gum (GG) and sodium alginate (SA) at various concentrations (e.g. between 0.1% to 5% biopolymer to soil mass ratio). The dependences of shear viscosity on water content, and undrained shear strength on water content were established. The results indicated that KG and SA increased the liquid limit (LL) of treated soils after the biopolymer content exceeded a certain limit (e.g. 0.5%), BG and GG contributed to a peak point in LL at biopolymer concentration of 1% to 2%, while XG and AG almost did not change the LL at all. The plastic limit (PL) was about 25% to 50% of the LL, leading to a trend of plasticity index (PI) similar to liquid limit. In order to further simplify the testing procedure and get the Atterberg limits for biopolymer-treated soil, one-point method was adopted.

1 Introduction

Civil engineering infrastructures are commonly constructed on weak or loose soils that requires improvement to resist applied loads [1-4]. In recent years, biopolymer, as directly utilised biogenic excrement, is characterized as one type of potential eco-friendly materials to be used for ground improvement. Biopolymers have been found to improve the soil strength significantly, even under a very low concentration (e.g. 0.5%) [5-6]. However, have an insight knowledge of soil consistency is important in understanding particle aggregation and water absorption characteristics of biopolymer treated soils for geotechnical applications. Nugent explained active nanoscale interactions between soil particles, cations, biopolymer and water from five different types of biopolymer treated soil to determine the liquid limit of the treated soil (e.g. XG, GG) [7]. Chen found that between 0 to 2%, a higher GG concentration lead to a higher LL, and the same situation for XG with a concentration between 0 to 3% [8]. Furthermore, Chang and Cho investigated beta-1,3/1,6-glucan treated Korean residual soil experimentally. It was found that a higher glucan content with the concentrations from 0% to 0.8% in the soil raised the LL linearly and the PL increased slightly from 37.4% to 52% [9]. Calvello et al. investigated that the liquid limit of three clayey soils prepared with formamide assumed values very close to those obtained with distilled water and liquid limit increased with the increase of dielectric constant of the pore fluid from 1 to 80 [10]. Chang explored the influence of pore-fluid variation on Atterberg limits of XG treated soils. It can be found that the xanthan gum behaviour in the deionized water was governed by clay-

mineral type, while the pore-fluid chemistry governed the xanthan gum behaviour in the brine and the kerosene [11].

In terms of clayey soil, biopolymer-to-clay content is more critical than biopolymer-to-total soil content due to electrostatic and chemical bonding characteristics between biopolymers and clay particles [7, 11]. Therefore, the soil consistency of biopolymer treated clay with various biopolymer types and a wide range of biopolymer concentrations should be further comprehensively explored to meet the gap for geotechnical engineering application.

In this study, six typically biopolymers extracted from plants, metastatic products of microorganism, or cell walls of algae easily, which have been widely used in certain fields (e.g. food, paint, oil exploration) and are the potential materials in the application of civil engineering infrastructures, were adopted to treat soil with a wide concentrations range from 0.1% to 5%. The general results about Atterberg limits of biopolymers treated soil were investigated by using fall cone test.

2 Materials and Method

2.1 Materials

The Kaolinite used in this experimental study was quarried from the South West of England. The clay grains were mainly composed of 47% of SiO₂ and 38% of Al₂O₃, respectively. Table 1 summaries the specific physical parameters of the kaolinite.

Six biopolymers, e.g. carrageenan kappa gum (KG), locust bean gum (BG), xanthan gum (XG), agar gum (AG), guar gum (GG) and sodium alginate (SA) supplied

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by Special Ingredients Ltd were used in the present study.

Table 1. Basic physical parameters of kaolinite.

| | |
|---|-----------|
| Soil type | Kaolinite |
| $D_{60}/\mu\text{m}$ | 0.976 |
| $D_{30}/\mu\text{m}$ | 0.4 |
| $D_{10}/\mu\text{m}$ | 0.247 |
| Specific surface area (m^2/g) | 14 |
| C_u | 3.95 |
| C_c | 0.66 |
| $PL/\%$ | 30.7 |
| $LL/\%$ | 69.9 |
| $PI/\%$ | 39.2 |
| USCS | <i>CH</i> |
| Specific gravity | 2.6 |

2.2 Sample preparation and testing apparatus

2.2.1 Kaolinite-biopolymer mixture preparation

The clay was completely air dried in an oven at 105°C for 24 hours before a thorough mixing with each dry biopolymer. The biopolymer-over-solids from soil mass ratio (m_b/m_s) for biopolymer-soil mixtures was selected as 0.1~5%. Untreated soil, i.e., pure clay (PC) was also prepared as a reference as shown in Table 2.

Table 2. Treatment conditions of biopolymer-clay mixture.

| Biopolymers | concentration (m_b/m_s), % |
|-------------|---|
| PC | 0 |
| KG | 0.2, 0.5, 1.0, 2.0, 2.5, 3.0, 4.0, 5.0 |
| BG | 0.2, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0, 5.0 |
| XG | 0.1, 0.2, 0.5, 1.0, 2.0, 2.5, 3.0, 4.0, 5.0 |
| SA | 0.2, 0.5, 1.0, 2.0, 2.5, 3.0, 4.0, 5.0 |
| GG | 0.2, 0.5, 1.0, 2.0, 2.5, 3.0, 4.0, 5.0 |
| AG | 0.1, 0.2, 0.5, 1.0, 2.0, 2.5, 3.0, 4.0, 5.0 |

2.2.2 Fall cone test

Fall cone tests were conducted to determine the liquid limit and plastic limit of biopolymer-treated kaolinite by using a cone with 80g weight and 30° tip angle, and a sample cup with 55 mm diameter and 40 mm height [12]. And the fall cone test was repeated at least four times with various water contents for each treatment condition to determine the Atterberg limits.

3 Results and discussion

3.1 Results of Atterberg limits

The relationship between the logarithmic water content (w) and the logarithmic cone penetration (d) was found to be linear for any soil types [13-14] as given by Eq. (1).

$$\lg w = \lg c + m \lg d \quad (1)$$

where c is the water content at a penetration depth of 1 mm and m is the slope of the linear relationship. The water content corresponding to 20 mm and 2 mm can be regarded as the liquid limit (LL) and plastic limit (PL), respectively [12]. The variation of liquid limit, plastic limit and plasticity index ($PI=LL-PL$) with biopolymer contents for soils treated with six biopolymers are shown in Fig. 1.

As shown in Fig. 1 (a) and (d), the liquid limit of KG or SA-treated kaolinite increases linearly up to $m_b/m_s = 5\%$ (stage ②) after m_b/m_s exceeded certain values, i.e., $m_b/m_s = 0.5\%$ to 1% (stage ①). The plastic limit of KG-treated soil kept almost constant at 30% for $m_b/m_s < 3\%$ and then increases linearly with the increase of KG content, while the plastic limit of SA-treated kaolinite remains around 50% in the range from 0.5% to 4%. For high-plasticity clays, the plastic limit is much smaller than the liquid limit and therefore the plasticity index is dominated by the liquid limit and the plastic limit provides limited additional information for the purposes of clay classification [12, 15].

As shown in Fig. 1 (b) and (e), LL fluctuates with the increase of BG or GG content. To be specific, LL initially increases (stage ①) to a peak point (m_b/m_s is between 1% to 2%) decreases to an inflection point (stage ② m_b/m_s is between 2% to 3%), and then slightly increased up to $m_b/m_s = 5\%$ (stage ③). The overall trend of the plastic limit increases with the increasing BG or GG content. However, as PL is only 20% to 50% of LL , the PI trend of BG or GG-treated soil is similar to that of LL .

As to XG or AG-treated kaolinite, the liquid limit changed slightly. XG-treated kaolinite had a maximum liquid limit at $m_b/m_s = 0.5\%$ and a descending phase afterwards, while AG-treated kaolinite had an almost constant liquid limit. Moreover, the plasticity limit remains roughly 50% of the liquid limit.

3.2 Mechanism

The difference between the effectiveness of six biopolymer types in increasing the LL of kaolinite is attributed to the variety in viscosities of biopolymer solutions and aggregation levels of kaolinite particles. Podsiadlo showed that organic polymers can form a highly linked and extensive biopolymer-clay network through hydrogen bonding [7]. Therefore, biopolymer interaction with pore-fluid forms hydrogel with a high viscosity increases the liquid limit. On the other hand, biopolymer-induced aggregation of clay particles via

cation bridging and hydrogen bonds tends to decrease the liquid limit. As clay particles aggregating, the surface area of the clay decreases, therefore, less liquid is required to fully hydrate the surfaces of the soil particles [16].

3.3 Soil classification

Plasticity index and liquid limit are frequently adopted to classify and estimate the behaviour of natural soils in

geotechnical engineering. The *LL-PI* plane is plotted in Fig. 2. It illustrates that most of the samples can be considered as silt falling below *A* line. Others are classified as clay falling between *U* line and *A* line. The soil plasticity tends to increase owing to the biopolymer-induced formation of viscous hydrogel, while decreasing due to elevated clay particle aggregation. Therefore, both biopolymer types and contents have an effect on soil classification.

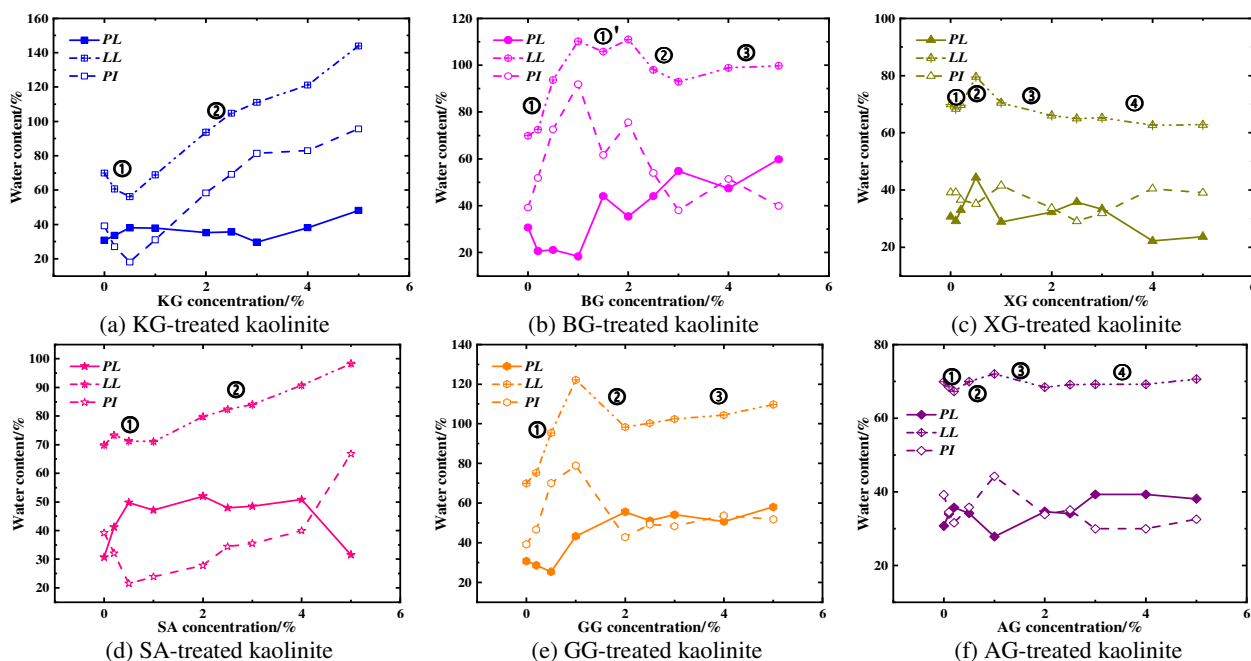
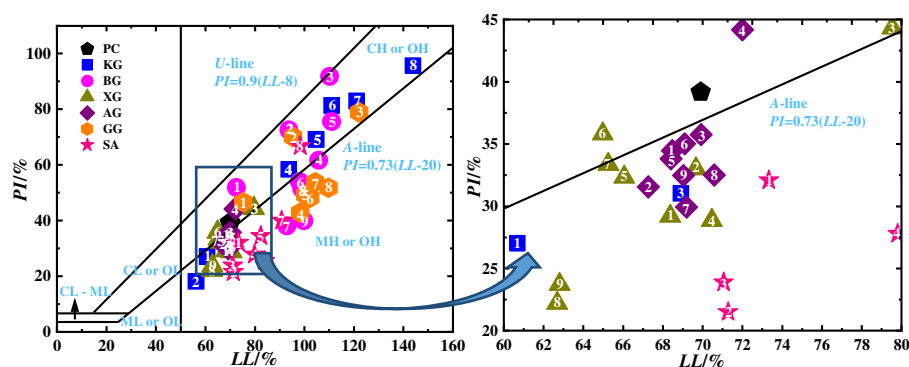


Fig. 1. Consistency limits versus biopolymer concentration



| | 0 | 0.1 | 0.2 | 0.5 | 1.0 | 1.5 | 2.0 | 2.5 | 3.0 | 4.0 | 5.0 |
|----|---|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| PC | ● | | | | | | | | | | |
| KG | | | 1 | 2 | 3 | | 4 | 5 | 6 | 7 | 8 |
| BG | | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| XG | | 1 | 2 | 3 | 4 | | 5 | 6 | 7 | 8 | 9 |
| AG | | 1 | 2 | 3 | 4 | | 5 | 6 | 7 | 8 | 9 |
| GG | | | 1 | 2 | 3 | | 4 | 5 | 6 | 7 | 8 |
| SA | | | 1 | 2 | 3 | | 4 | 5 | 6 | 7 | 8 |

Fig. 2. Chart for the classification of soils used in this study based on USCS.

3.4 One-point method determining liquid limit

Determination of liquid limit of soils using only one value of cone penetration and its water content was proposed by many researchers [13-14, 17]. This method is beneficial for evaluating the liquid limit when the soil sample and time availability for the testing are limited. Equation (1) can be rewritten to form a one-point fall cone method to determine the liquid limit as follows.

$$w = c(d)^m \quad (2)$$

Since LL is the water content corresponding to 20 mm,

$$LL = c(20)^m \quad (3)$$

Dividing Eq. (2) by Eq. (3), one obtains

$$\frac{LL}{w} = \left(\frac{20}{d}\right)^m \quad (4)$$

With a set of data (d , m) from a fall cone test, the liquid limit can be computed using Eq. (4) with a given value of m . The test results of water content versus the cone penetration ranging from 15 mm to 25 mm are shown in Fig. 3. The slope m has a maximum value of 0.6, a minimum value of 0.17, and an average value of 0.35 as shown in Fig. 4.

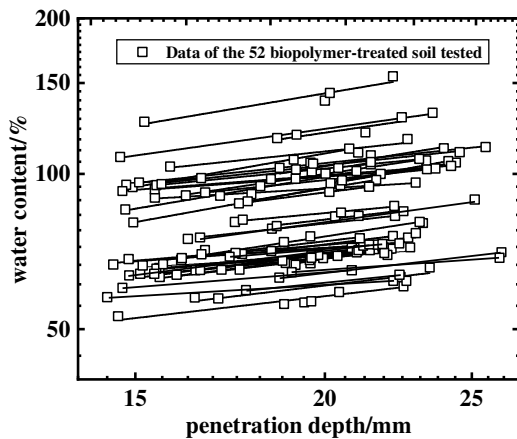


Fig. 3. Measured flow curves for determination liquid limit.

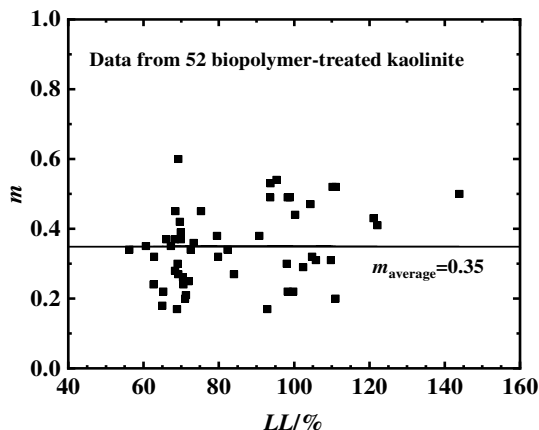


Fig. 4. Empirical data versus the parameter m .

Moreover, the ratios of LL (one-point method) to LL (four-point method) ranges from 0.93 to 1.07 for all biopolymer-treated soils as shown in Fig. 5. On the other hand, the difference between the LL (one-point method) and LL (four-point method) versus LL (four-point method) shows that the maximum difference is around 4%. Therefore, it is clear that Eq. (4), with an m value of 0.35, can be used to estimate the liquid limit of biopolymer-treated kaolinite by one fall cone test with cone penetration falling between 15 and 25 mm.

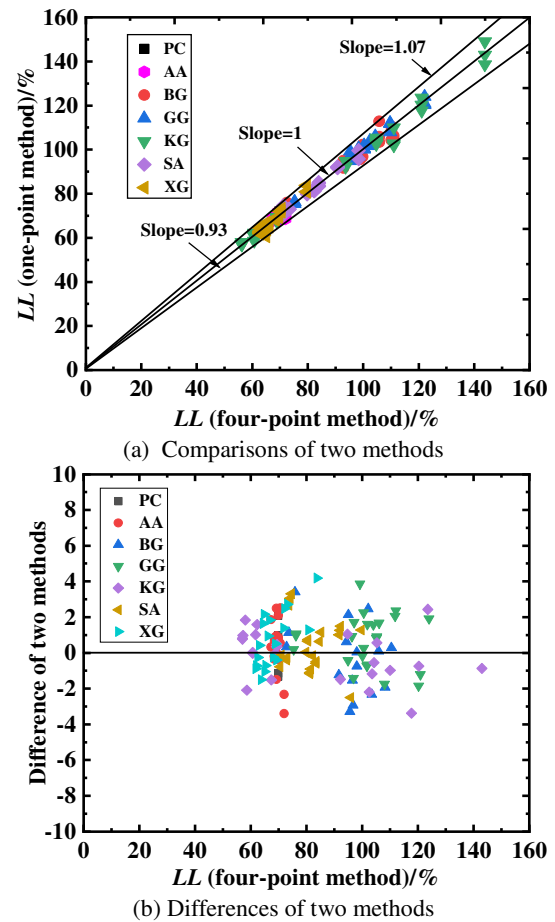


Fig. 5. Comparisons and differences of two methods.

4 Conclusions

Biopolymer has contrary effects on the soil consistency. On the one hand, biopolymer induces particle aggregation contributing to the decrease of liquid limit. On the other hand, the liquid limit of biopolymer treated soils increases due to the formation of biopolymer hydrogel. In general, KG, BG and GG are more effective than XG, AA and SA in increasing the liquid limit of kaolinite. The soil characteristics of KG and SA-treated kaolinite is transferred from silt to clay with the increase of biopolymer content. However, XG and AG-treated kaolinite falls around A line within the biopolymer concentrations of 5%. Finally, one-point method with the slope $m=0.35$ of water content versus penetration is recommend predicting the liquid limit of biopolymer-treated kaolinite.

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